

ESTIMATING COARSE SEDIMENT TRANSPORT
IN MOUNTAIN WATERSHEDS

BY

DONALD O. DOEHRING
FRANK G. ETHRIDGE

Lewis
4/4/79

FINAL REPORT

EISENHOWER CONSORTIUM
FOR
WESTERN ENVIRONMENTAL FORESTRY RESEARCH

CSU PROJECT 31-1482-1436
Eisenhower Consortium Project Contract No. 16-692-6R,
EC#221

ESTIMATING COARSE SEDIMENT TRANSPORT
IN
MOUNTAIN WATERSHEDS

Prepared by:



Donald O. Doehring
Associate Professor



Frank G. Ethridge
Associate Professor

Department of Earth Resources
College of Forestry and Natural Resources
Colorado State University
Fort Collins, Colorado 80523

I. INTRODUCTION AND STATEMENT OF OBJECTIVES

The research reported here was conducted under two grants from the Eisenhower Consortium for Western Environmental Forestry Research (EC#186 and EC#221) and was performed from April, 1976 through December, 1978. In addition to the funding provided by the Eisenhower Consortium, the authors wish to gratefully acknowledge assistance from Mr. Dave Rosgen, U. S. Forest Service, Roosevelt National Forest; the College of Forestry and Natural Resources, Colorado State University; Drs. Dave Foster and Vic Hasfurther, Department of Civil Engineering, University of Wyoming; and Mr. Michael D. Harvey, Department of Earth Resources, Colorado State University.

The work reported here was conducted under the supervision of Drs. Doehring and Ethridge by Mss. Donald H. Simpson, Henry G. DeWitt, David R. Haddock, and Richard C. Moore.

The primary objectives of the project are to:

- 1) develop a procedure for estimating sediment discharge given hydrologic, morphometric and sedimentologic inputs,
- 2) estimate the median bedload size moved by floods of various return periods,
- 3) develop the capability to estimate bedload sediment movement for given grain sizes under given hydrologic conditions, and
- 4) test the applicability of the Pfankuch-Rosgen channel stability technique for estimating sediment yield in the Roosevelt and Medicine Bow National Forests.

II. DESCRIPTION OF THE STUDY AREA

The principal study area consists of the drainage basin of the South Fork of the Cache la Poudre River, Roosevelt National Forest, Colorado (Figure 1). In addition, some data were collected in the drainage basins of the North Fork of the Little Laramie River, Medicine Bow National Forest, Wyoming and the Middle and South Forks of the St. Vrain River, Roosevelt National Forest, Colorado.

Since the majority of the field studies were concentrated in the South Fork of the Cache la Poudre River, this drainage will be described in greatest detail. The total area enclosed by the basin is 102.7 square miles and the length of the main channel above the lowest study site is 24.1 miles. Total relief within the drainage basin is 6850 feet, and the average gradient along the South Fork is 217 feet/mile (Figure 2).

The drainage basin of the South Fork of the Cache la Poudre is underlain primarily by Precambrian igneous and metamorphic rocks. Thick deposits of

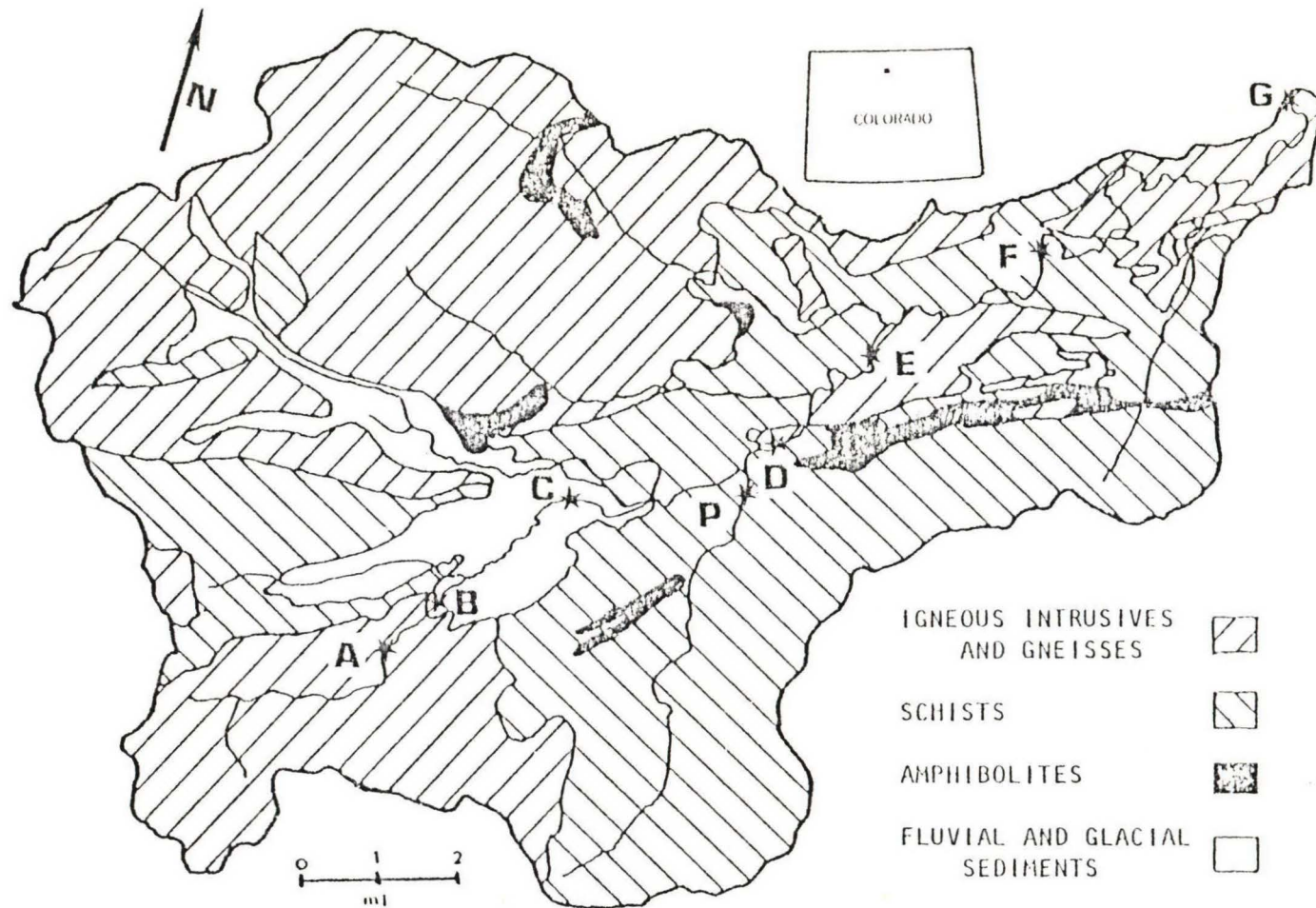


Figure 1. Generalized lithologic map of the Little South Fork of the Cache la Poudre River showing study site locations.

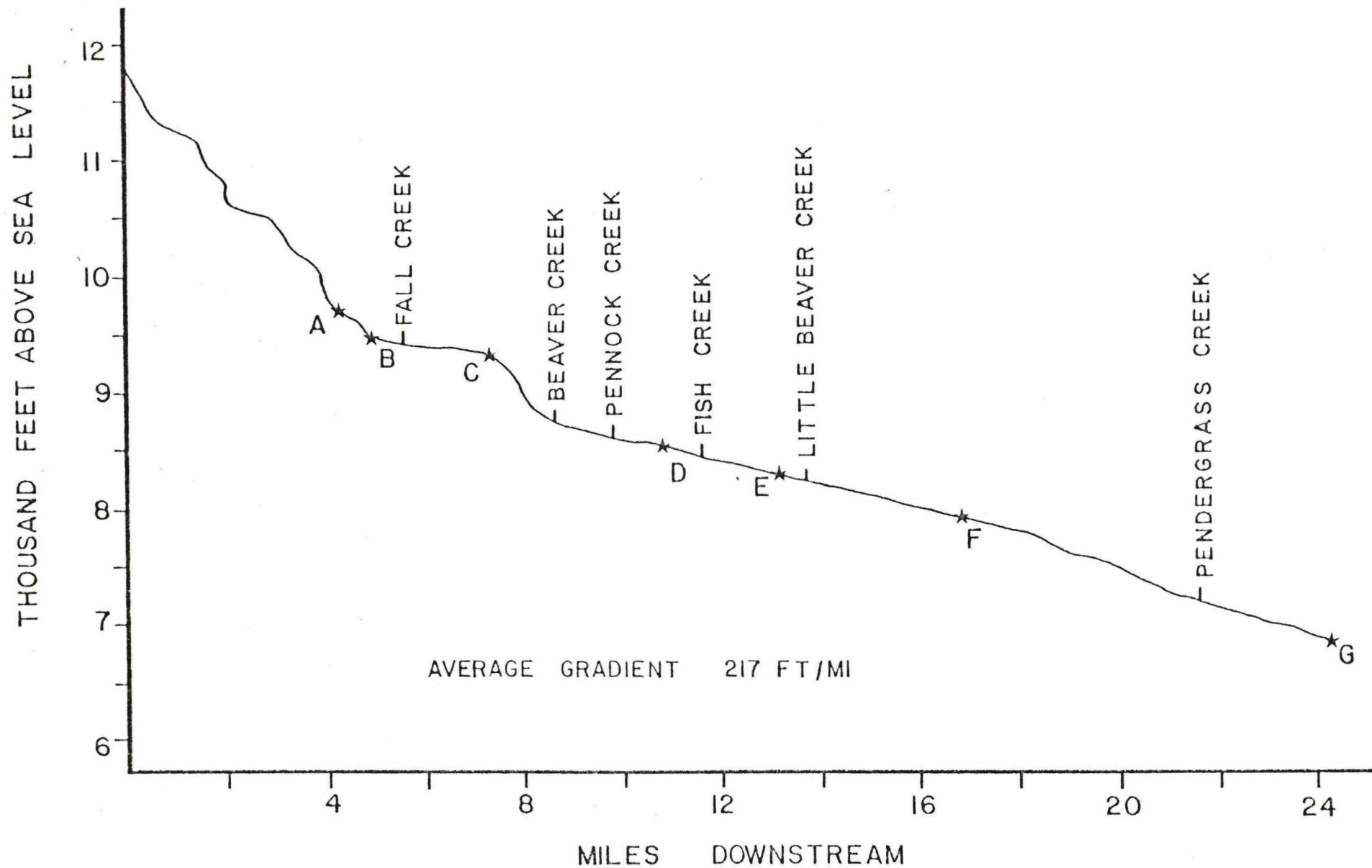


Figure 2. Longitudinal profile of the South Park of the Cache la Poudre River in the study area showing main channel sample locations (stations) and tributaries. (Vertical exaggeration approximately 12X).

unconsolidated Quaternary stream and glacial sediments are common only along and adjacent to the river and its tributaries. At least one large Precambrian fault zone (Skin Gulch Shear Zone) traverses the study area in a southwest-northeast direction. The fault zone intersects the Precambrian Poudre Shear Zone immediately northeast of the study area. The course of Fish Creek and the middle portion of the South Fork appear to be controlled by the trend of the Skin Gulch Shear Zone.

Bedrock materials present can be subdivided into four types based on erodability. These are: 1) igneous intrusives and gneisses, 2) schists, 3) amphibolites, and 4) fluvial and glacial deposits. It appears that drainage densities reflect the relative erodability of the lithologic units within the watershed. They are relatively low in areas underlain by igneous intrusive rocks and gneisses and moderate to high for areas underlain by schists and amphibolites. Drainage densities are also high within interbasins and other areas underlain by Quaternary sediments which are more vulnerable to fluvial erosion.

Although the overall drainage densities found in the watershed are low, the valley sideslope values are high (31% - 55%). This is due, in part, to glacial erosion (and deposition) which has tended to widen valleys and increase slope angles. Steep slopes are also established in highly resistant rocks due to erosion along locally weaker faults and fracture zones.

Visual examination of the longitudinal profile of the South Fork (Figure 2) reveals that the river is not at grade. At least three different segments are obvious:

- 1) Above Pingree Park the river occupies a series of "stair steps" (nickpoints) cut into the igneous intrusives and gneisses. Gradients along this reach of the river range from 211 ft/mi to 1760 ft/mi which include some of the highest gradients along the entire South Fork.

- 2) In the vicinity of Pingree Park the river meanders through a filled glacial valley. Gradients in this reach average 77 ft/mi and are some of the lowest along the South Fork.

- 3) Below Pingree Park, gradients range between 115 and 71 ft/mi. Along this reach the South Fork constitutes a series of pools and riffles. Near the confluence of the Poudre River the gradient steepens to 1600 ft/mi. The increased gradient in this lower reach is attributed to recent faulting in the area.

This unusual stream profile is similar to those found on streams in the Sierra Nevada Mountains of California. Thus, it appears that, like the Sierra Nevada streams, the South Fork is still adjusting its stream profile to compensate for changes brought about by the recent glacial activity of the Quaternary Period.

The North Fork of the Little Laramie watershed is situated within the Medicine Bow National Forest approximately five miles northwest of Centennial, Wyoming. It drains an area of 9.7 square miles at the lowest study site. Maximum relief within the basin is 2,090 feet which results in an average stream gradient of 316 feet per mile. The longitudinal profile does not contain the prominent "stair-steps" associated with the Little South Fork. However, two subdued "stair-steps" appear along the upper mile of the profile. The nickpoints appear to be the result of glaciation.

The North Fork basin is underlain by Precambrian metamorphic rocks including gneisses, schists, slates, phyllites, quartzites and dolomites (Houston, 1968). Much of the basin is covered by Quaternary fluvial and glacial sediments.

Bedrock materials present can be subdivided into four types based on erodability and rock type. These are: 1) quartzites, 2) slates, schists, phyllites, and gneisses, 3) dolomites, and 4) fluvial and glacial deposits. Drainage densities do not reflect the relative erodability of the lithologic units within the watershed. The highest drainage densities occur in the resistant quartzites. This could be due to local faulting in the quartzite or the short time of drainage adjustment in the watershed due to recent glaciation.

The average valley-side slope for the watershed is 20% which is low for a mountainous terrain. This is due to the low drainage density and the rolling topography left as a result of glacial deposition in the area.

The longitudinal profile of the North Fork can be divided into three segments.

- 1) Above 10,200 feet the profile consists of some subdued "stair-steps". Gradients in this reach range from 88 feet per mile to 1,584 feet per mile.
- 2) Between 10,200 feet and 9,700 feet the stream has a convex-up profile. Gradients along this reach average 370 feet per mile.
- 3) Below 9,700 feet the profile contains some "stair-steps" but is predominately a concave-up profile. Gradients range from 65 feet per mile to 850 feet per mile.

The St. Vrain watershed, used for verification of our equations, encompasses almost 65 square miles of mountain terrain. It heads at the Continental Divide approximately 20 miles northwest of Boulder, Colorado. Maximum relief of the basin is 6,530 feet with an average stream gradient of nearly 400 feet per mile. Climatic data for this area probably approximates data for the Little South Fork due to its close proximity and elevation (highest point 13,440 feet -- lowest point 6,910 feet).

Bedrock of the region consists of granites, gneisses and schists of Precambrian age and a few Tertiary intrusives near the Continental Divide (Lovering and Goddard, 1950). Quaternary glaciation has altered much of the bedrock producing deep, east-west trending, U-shaped valleys containing prominent moraines. Till and fluvio-glacial deposits cover approximately 25 to 30 percent of the study area and appear to be a major source of sediment for the St. Vrain River. Madole (1969) believes that the area exhibits one of the best records of Pleistocene glaciation in the Front Range.

III. RESEARCH PROCEDURES

Seven stations along the South Fork of the Cache la Poudre and five stations along major tributaries were selected for study and evaluation. These sites were occupied 133 times during the previous three field seasons. A total of 259 bedload samples, 45 suspended load samples and 24 bank samples were collected. Table 1 gives a listing of samples by station and Figure 1 shows the location of each station within the drainage basin. Because of problems involving access to stations A and G during the 1977 field season and stations A, B, and G during the 1978 season and the limited amount of data from these stations, they are not included in the models for sediment discharge. Limited data were also collected from two sites along the North Fork of the Little Laramie River during the 1977 field season and from three sites along the Middle and South Forks of the St. Vrain River during the 1978 field season.

Each time a station was visited, the following information and samples were collected:

- 1) channel cross section, including channel depths and width;
- 2) water velocities across the transect using a Marsh-McBirney Model 201 electromagnetic current meter;
- 3) two bedload samples, using a modified Helley-Smith bedload sampler;
- 4) suspended load samples (collected periodically during the 1977 season);
and
- 5) water temperatures (collected periodically during the 1977 season).

Table 1. Numbers of bedload, suspended load and bank samples from each Station along the South Fork of the Cache la Poudre River (Note: Location of all stations given on Figure 1).

STATION	NO. OF TIMES STATION WAS OCCUPIED		NO. OF BEDLOAD SAMPLES		NO. OF SUSPENDED LOAD SAMPLES		NO. OF BANK SAMPLES
	1976-1977	1978	1976-77	1978	1977	1978	1977
A	5	-	10	-	2	-	-
B	13	-	25	-	6	-	-
C	14	9	28	18	9	-	6
D	11	10	22	20	4	-	6
E	15	9	29	18	12	-	6
F	12	7	22	14	4	-	-
G	4	-	8	-	3	-	6
(Pennock Creek)	11	9	20	18	3	-	-
Q (Fall Creek)	1	-	1	-	-	-	-
R (Fish Creek)	1	-	2	-	1	-	-
S (Little Beaver Creek)	1	-	2	-	-	-	-
T (Beaver Creek)	1	-	2	-	1	-	-
Totals for each snow-melt runoff period	89	44	171	88	45	0	24
Grand Totals	133		259		45		24

Figure 3 is a sample data sheet which was completed each time a station was visited.

A detailed survey of the morphology of six of the sample stations have been completed, using plane table and hand level techniques. The rating of each stream reach along a station using the channel stability rating scheme of Pfankuch (1975) and a photographic record of each station has been completed.

All 259 bedload samples from the South Fork of the Cache la Poudre River have been weighed and those samples weighing more than 3 grams have been sieved to obtain grain size statistics. In addition, eighty-five bedload samples obtained by Dave Rosgen, Hydrologist, Roosevelt National Forest, 3 samples from the North Fork of the Little Laramie River, and 12 samples from the Middle and South Forks of the St. Vrain River have been weighed and sieved. Finally, twenty-four (24) bank samples from the South Fork watershed have been weighed and sieved and all suspended load samples have been dried and weighed to obtain the concentration of the total solids in milligrams per liter.

The granule, very coarse sand, coarse sand, medium sand, and fine sand fractions of selected bedload samples representing various discharges were prepared, and thin sections were made. Point counts of each thin section were made to determine the composition. In all, a total of 139 samples from the South Fork and the Poudre have been petrographically analyzed. For a complete description of these procedures and a compilation of all compositional data the reader is referred to DeWitt (1978).

Standard U. S. Geological Survey 7½ minute topographic quadrangles with a scale of 1:24,000 were selected as base maps for collection of morphometric data. Data collected and calculated from these maps include watershed area (A_b), total stream length (L), source index (SI), drainage density (D_d), maximum relief (H), valley side slope (S_g), ruggedness number (HD_d), geometry number ($HD_d/\tan[S_g]$), gradient index (SL) and relief ratio (R_n).

Hydrologic and morphologic field data collected at each station were used to determine discharge and total stream power. Discharge was calculated by determining the area between adjacent depth measurements and multiplying by the average velocity taken at adjacent depth measurements. The continuity equation ($Q = \bar{V}A$) was then applied to compute the total discharge for each cross section. Cross sectional area (A) and wetted perimeter (P) were measured from plotted cross sections. The hydraulic radius (R) was also computed. Total stream power (Ω) was then calculated as the product of $\gamma R S \bar{V} W$; where γ is the unit weight of water (62.4 lb/ft^3), $\bar{V}$ is the average velocity (ft/sec), W is the stream width in feet, S is the slope of the water surface, and R is the hydraulic radius.

STATION NO.: _____ DATE: _____ RECORDER: _____

I. CROSS SECTION DATA: (DIST. from left bank looking downstream)

DIST.	0	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25
DEPTH																										
DIST.	26	27	28	29	30	31	32	33	34	35	36	37	38	39	40	41	42	43	44	45	46	47	48	49	50	51
DEPTH																										
DIST.	52	53	54	55	56	57	58	59	60	61	62	63	64	65	66	67	68	69	70							
DEPTH																										

Channel width: _____ ft.

II. VELOCITY READINGS:

(a.) DIST. FROM LEFT BANK:				(c.) DIST. FROM LEFT BANK:			
DEPTH .3:	sec.	_____	clicks	DEPTH .3:	sec.	_____	clicks
DEPTH .6:	sec.	_____	clicks	DEPTH .6:	sec.	_____	clicks
DEPTH .2:	sec.	_____	clicks	DEPTH .2:	sec.	_____	clicks
AVERAGE VELOCITY	ft./sec.	_____		AVERAGE VELOCITY	ft./sec.	_____	
(b.) DIST. FROM LEFT BANK:				(d.) DIST. FROM LEFT BANK:			
DEPTH .3:	sec.	_____	clicks	DEPTH .3:	sec.	_____	clicks
DEPTH .6:	sec.	_____	clicks	DEPTH .6:	sec.	_____	clicks
DEPTH .2:	sec.	_____	clicks	DEPTH .2:	sec.	_____	clicks
AVERAGE VELOCITY	ft./sec.	_____		AVERAGE VELOCITY	ft./sec.	_____	

III. DISCHARGE FOR CROSS SECTION: Q=VA Q= _____ cusec.

IV. TEMPERATURE (IF DETERMINED): _____ °C

_____ °F

V. BED LOAD SAMPLES:

(a.) 30 sec. samples (max. of 20): Sample No.: _____
 No. of 30 sec. intervals in this sample _____
 Total sample wt. _____ gms. Sample Med. Size _____ gms.

(b.) Longer sample (5 min. sample in Talweg):

Loc. of Sample (FT. from Left Bank) _____ ft. Sample No.: _____
 Sample wt. _____ gms. Sample Med. Size _____ phi

VI. SUSPENDED LOAD SAMPLES:

(a.) DISTANCE from left bank _____ ft. Sample no. _____
 Sample wt. _____ gms.

(b.) DISTANCE from left bank _____ ft. Sample no. _____

Sample wt. _____ gms.

VII. COMMENTS (Use back of page)

Figure 3. Sample data sheet for recording data from stations along the South Fork Cache la Poudre River and tributaries.

Bedload discharge rates (Q_s) were calculated using the average weight of the two bedload samples collected each time a station was occupied, and the channel width according to the following equation:

$$Q_s = \frac{\overline{wt} \times W}{150},$$

where, $\overline{wt}$ is the average weight of the two samples in pounds and W is stream width in feet.

IV. RESULTS

A. Objective 1, Sediment discharge model

Developing a bedload transport model requires an understanding of basic theory for the proper selection of independent variables. A simplistic philosophy states that two primary conditions must be met in order for sediment within a watershed to become a part of the bedload. First, there must be processes that deliver the sediment to the stream; and second, the stream must have the competency to move the sediment (Einstein, 1964; Simons and Sentürk, 1977). These conditions then, act as limits on the bedload transport rate.

In the case of armored channels found in mountain streams it is the sediment supply that limits bedload transport (Nanson, 1974). The stream may have sufficient energy to support a large amount of a certain size material; but if that material is protected by channel armoring or is incorporated into the banks, it will require a flow with sufficient energy to disrupt the armoring or with sufficient stage to produce bank erosion to set the sediment in motion. Hydrologic components can model these processes as well as the aforementioned stream competency factor. But another process which must also be considered is the ability of the watershed to supply sediment to the stream. Watershed morphology reflects this process. Therefore, both hydrologic and morphometric parameters are used in this study.

The hydrologic parameters used as independent variables are water discharge and total stream power. Water discharge is indicative of the stream's ability to move sediment. It also reflects channel cross section because higher discharges usually correlate with higher stage. This is especially important when the discharge reaches bankfull or near bankfull stage, because at this point, water discharge also models sediment available to the stream from the banks. Total stream power is closely related to water discharge but may be a better predictor of bedload discharge for two reasons. Total stream power contains a hydraulic radius component which represents the proportion of the cross section that is the actual riverbed. It also contains a slope component which reflects energy available for bedload transport.

The morphometric variables used as input to the models are drainage density, source index, ruggedness number, and relief ratio. These variables are used as an indirect indication of the processes involved in supplying sediment to the stream. Drainage density, for example, is often taken as an index of rock type erodability. High values generally represent areas of highly erodable rock and soil, while low values of drainage density indicate materials of low erodability. Drainage density also reflects the total length of streambanks along which riparian erosion can take place per unit watershed area.

The number of drainage network sources per unit area (source index) may also be looked upon as the number of sediment sources per unit area. A region with a large source index should produce more sediment than a region with a smaller index.

The relief ratio is a dimensionless number that approximates the overall watershed slope (Lustig, 1965). Steeper watersheds are able to generate more energy within the hydrologic factors and therefore are usually able to yield more sediment than watersheds with low relief. This is especially true for areas of nearly unlimited sediment supply.

The ruggedness number is a combination of relief and drainage density.

To evaluate the selected independent variables as predictors of bedload transport a stepwise linear regression procedure was initially chosen. Data from all study sites were included in the program. At each step, stepwise regression adds the independent variable that will make the greatest reduction in the error sum of squares. At each step it also checks to insure statistical significance of all entered variables. It is therefore considered to be one of the best methods for obtaining good statistical models (Draper and Smith, 1966). Using an F-value of 3.84 ($\alpha = .05$) a model was obtained that used five independent variables to explain 78% of the variability in bedload discharge. This model contained independent variables which were colinear and may have been artificially showing statistical significance when it was unwarranted. In addition, five independent variables in the model provides a very complex equation. For these reasons the model was discarded.

As a second approach the data were evaluated by a fast screen regression process. A fast screen program calculates Coefficients of Determination for all possible combinations of independent variables in univariate multiple linear regression. This procedure gives an abbreviated look at the n best, k -variable regressions, for $k = 1, 2, \dots, n$, where n is the number of independent variables. The equations are evaluated on the basis of their Coefficients of Determination

Table 2. Statistical properties of the predictive equations

Equation number	Equation	R^2	S_e
(1)	$\text{Log } Q_s = -5.97 + 1.45(\text{log } Q_w) + .35 (D_d)$	68%	31%
(2)	$\text{Log } Q_s = -2.87 + 1.10(\text{log } \Omega) + .002 (Q_w)$ $- .00006(HD_d)$	75%	28%
(3)	$\text{Log } Q_s = -7.53 + 1.34(\text{log } \Omega) + .002 (Q_w)$ $+ .179(SI) + .002 (R_h)$	77%	27%

<u>Symbol</u>	<u>Definition</u>	<u>Units</u>	<u>Range of Values Used</u>
Q_s	bedload discharge	lbs./sec.	-----
Q_w	water discharge	c.f.s.	1.7 - 754
D_d	drainage density	mi./sq. mi.	3.48 - 5.57
Ω	total stream power	lbs./sec.	0.54 - 560
HD_d	ruggedness number	ft.mi./sq.mi.	14,700 - 23,900
R_h	relief ratio	ft./mi.	415 - 961

(R^2). Additional information supplied for each equation are the total corrected sums of squares for Y , and a graphical representation of the types and relative magnitudes of error (bias or random). Finally, a controlled stepwise regression procedure was used to insure that the equations produced by the fast screen process were significant at an F-value of 3.84 (i.e., $\alpha = .05$) and to obtain coefficients for the independent variables.

Based on the information given by the fast screen and the controlled stepwise procedures, the following equations were selected:

$$(1) \quad \text{Log } Q_s = -5.97 + 1.45(\text{log } Q_w) + .35(D_d),$$

$$(2) \quad \text{Log } Q_s = -2.87 = 1.10(\text{log } \Omega) + .002(Q_w) - .00006(HD_d),$$

$$(3) \quad \text{Log } Q_s = -7.53 + 1.34(\text{log } \Omega) + .002(Q_w) + .179(SI) + .002(R_h).$$

Where, Q_s is bedload discharge, Q_w is water discharge, D_d is drainage density, Ω is total stream power, HD_d is ruggedness number, SI is source index, and R_h is relief ratio. The Coefficient of Determination (R^2), and Standard Error of the Estimate (S_e) associated with each equation are presented in Table 2. R^2 values for the selected equations range from 68 to 77%. The Standard Errors of the Estimates are expressed as a percentage of the mean response and range from 27 to 31%.

Criteria for selecting Equations 1, 2, and 3 as possible "best" models were high Coefficients of Determination, low standard errors, and a small bias error. Since the differences in these values for the models are not appreciable, alternative methods for determining the optimum equation were considered.

Sensitivity analysis is often used at this stage to evaluate the sensitivity of the model response to changes (or errors) in the independent variables (e.g., Simpson, 1973). The ideal model will consist of parameters that are sensitive enough to detect changes in process, but not so sensitive that small errors associated with measurement of the parameters produce large errors in the model's response. In this study a sensitivity analysis was performed on the three alternative equations to determine the sensitivity of their components. The computational procedure to derive the sensitivity values consisted of changing the value of one component by a given percentage and noting the effect this change produced on the model response. The change in model response was then converted to a percentage of the mean model response (i.e., the model response calculated using the mean values of the independent variables).

It was found that both Equations 2 and 3 contain components of little sensitivity, and Equation 3 contains a very sensitive component of little value to the total model. Therefore, Equation 1 was selected as the most appropriate model.

The "best" model should also minimize complexity and minimize the cost of data collection. Equation 1 is also the most satisfactory from these points of view. It requires gathering data for only two components, and may not require field work if water discharge data can be obtained from U. S. Geological Survey gauging stations or some other source. The drainage density component may be computed as an office procedure from standard U.S.G.S. topographic maps. Since Equation 1 is statistically valid, neither oversensitive nor undersensitive, and simple and conceptually correct, it is deemed the "best" model.

Equations 1, 2, and 3 record a least-squares fit of certain measured parameters in the Little South Fork of the Cache la Poudre watershed to bedload discharge for that particular drainage basin. The mathematical models say nothing of their applicability to other watersheds. As a test of their applicability, bedload measurements were taken on the Middle and South Forks of the St. Vrain River, and bedload discharges were calculated for those drainages from Equations 1 and 3. Bedload discharge was not calculated from Equation 2 because the ruggedness number obtained for the St. Vrain drainage was much higher than any values obtained on the Little South Fork. Use of data outside of the range used to obtain the predictive model violates one of the fundamental principles of regression analysis.

In addition, bedload for the St. Vrain was calculated from traditional equations of Schoklitsch (1934) and Meyer-Peter and Müller (1948). Observed values of bedload discharge are compared with predictions from Equations 1 and 3, as well as with the Meyer-Peter Müller and Schoklitsch formulas in Figures 4 and 5. The 95% confidence interval for the predicted values of Equations 1 and 3 are also depicted. In all cases, the observed values fall within the confidence intervals of the predicted values. Predictions from Equation 1 predict the observed values. In the worst case, Equation 1 under-predicts the observed values by 60%. This compares very favorably with either the Schoklitsch or Mayer-Peter and Müller formulas which over-predict by orders of magnitude. The reason for these overpredictions is most likely the assumption of unlimited sediment supply that underlies both of the traditional formulas.

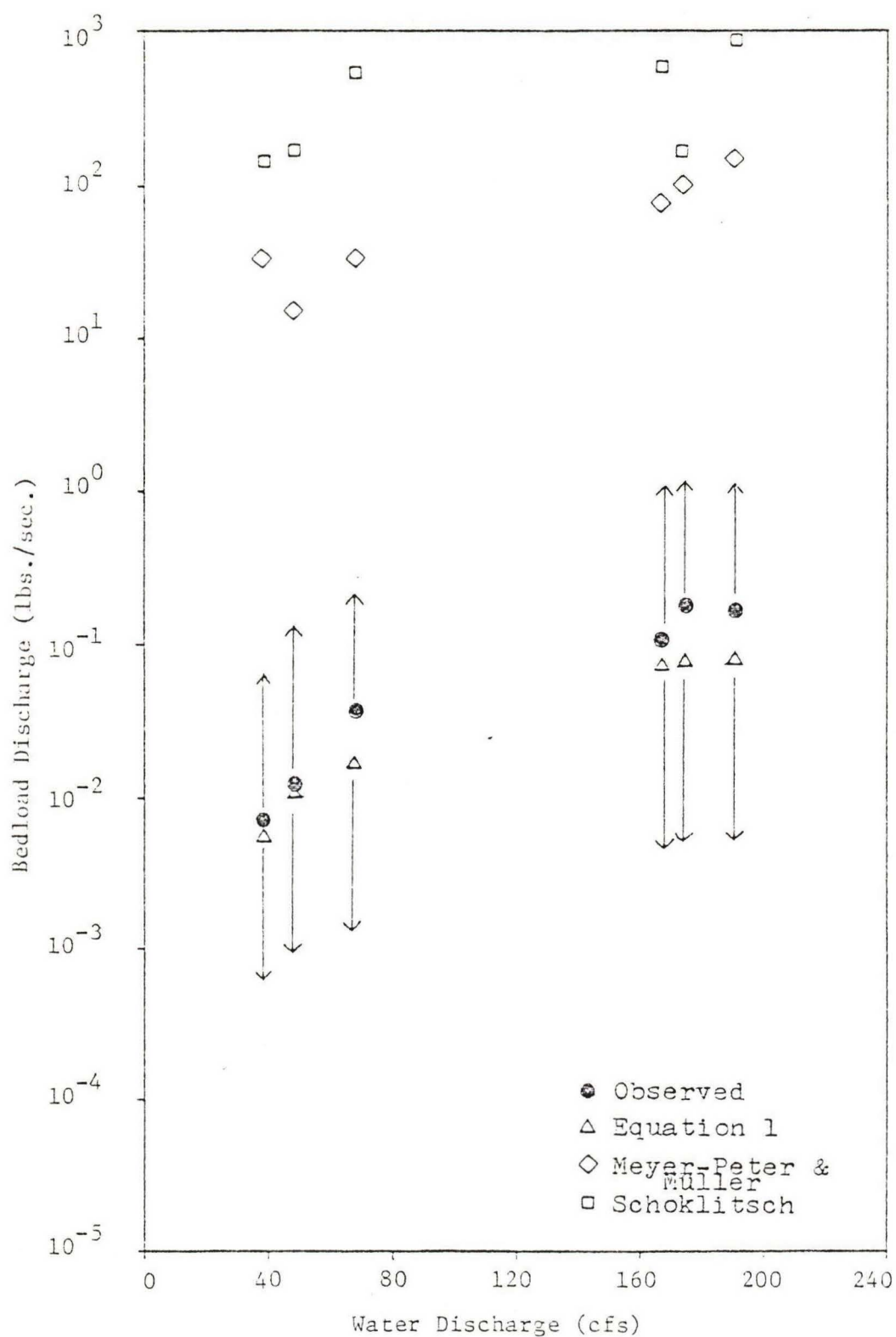


Figure 4. Comparison of traditional bedload formulas and Equation 1 with observed values on the St. Vrain River. Arrows indicate 95% confidence intervals for values predicted by Equation 1.

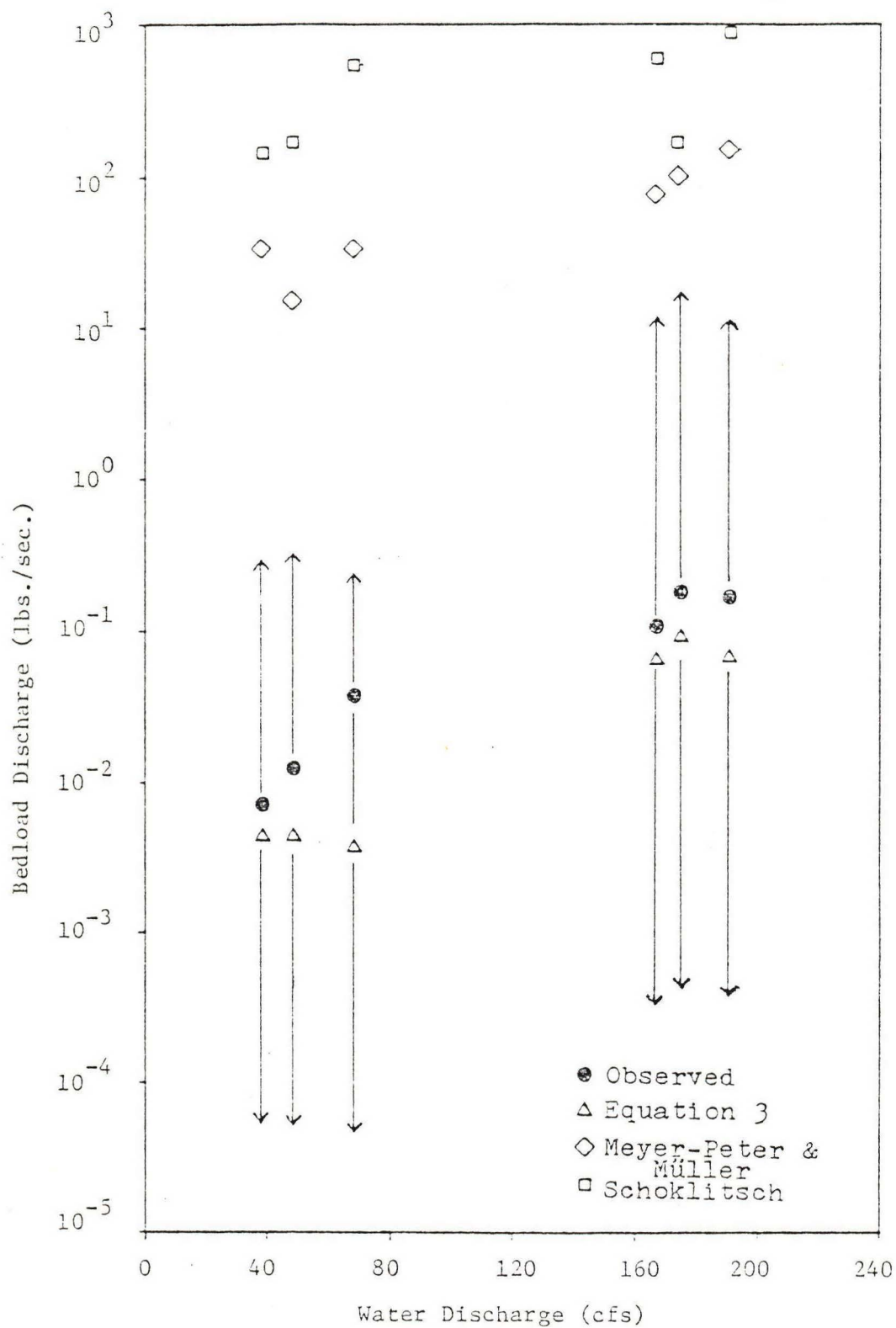


Figure 5. Comparison of traditional bedload formulas and Equation 3 with observed values on the St. Vrain River. Arrows indicate 95% confidence intervals for values predicted by Equation 3.

It is noteworthy that both equations developed on the Little South Fork in this study consistently underpredict the observations of the St. Vrain River. Upon further examination of the data, a possible explanation for this phenomenon was discovered. Geologic maps of the St. Vrain River above the lowest study site show an extraordinary amount of glacial sediments (Lovering and Goddard, 1950; Madole, 1969) when compared with the Little South Fork watershed. Hypothetically, these unconsolidated sediments could increase the sediment available to the stream by a process which is underestimated or unexplained by the morphometric variables of the models. It is also important to note that the study sites in the St. Vrain are in an area of more intense second home development than the South Fork.

B. Objectives 2 and 3.

A detailed investigation of the relationships among bedload grain size parameters, water discharge (Q_w), sediment discharge (Q_s), and stream power (Ω) permits certain generalizations to be made with respect to bedload sediment movement in mountain streams. These generalizations are valid only for the South Fork of the Cache la Poudre River and other streams that have similar geologic, geomorphic, and climatic characteristics.

There is a positive linear relationship between mean grain size (M_z) and water discharge (Q_w), between mean grain size (M_z) and stream power (Ω), and between maximum grain size (max) and water discharge (Q_w). The negative slopes and correlation coefficients given below for these relationships are a function of the phi (ϕ) scale used to record grain size values. An increase in phi values represents a decrease in grain size. Along main channel stations D, E, and F mean grain size is best predicted by $M_z = 0.55 - 0.0031 (Q_w)$ (Figure 6) which has a correlation coefficient of -0.67 and an associated coefficient of determination of 45% . Mean grain size is also predicted by $M_z = 0.4538 - 0.0043 (\Omega)$, however, this relationship has a coefficient of determination of only 40% . Maximum grain size is best predicted by $Max = -1.637 - .0046 (Q_w)$ (Figure 7) which has a coefficient of determination of 69% . When data from upstream channel locations are included these relations break down and the scatter of points about regression lines increases significantly, particularly for low discharges which reveal a number of large mean grain size values at relatively low discharges. Regression relations and correlation coefficients calculated for each station (D, E, and F) separately reveals similar slopes but consistent increases in the correlation coefficients as distance downstream increases (Table 3). Upstream from Stations D,

Table 3. Regression relationships for Mz vs. Qw, Mz vs. Q, and Max vs. Qw for individual stations and for stations D, E, and F combined. General form of the regression relationships is $Y = b + MX$.

STATION DESIGNATION	DISTANCE DOWNSTREAM IN MILES	b	m	r
<u>Mz vs. Qw</u>				
D	11.5	0.55	-0.0033	-0.62
E	14.1	0.35	-0.0032	-0.71
F	17.5	0.80	-0.0034	-0.82
D+E+F	-	0.55	-0.0031	-0.67
<u>Mz vs. Q</u>				
D	11.5	0.47	-0.0038	-0.55
E	14.1	0.23	-0.0052	-0.63
F	17.5	0.71	-0.0046	-0.74
D+E+F	-	0.45	-0.0043	-0.63
<u>Max vs. Qw</u>				
D	11.5	-1.72	-0.0047	-0.73
E	14.1	-1.83	-0.0044	-0.83
F	17.5	-1.35	-0.0048	-0.91
D+E+F	-	-1.64	-0.0046	-0.83

E, and F, in the glaciated portion of the drainage basin, sufficient bedload and discharge data to determine relationships are available only for station C. The relationship between M_z and Q_w for station C is best expressed by the linear function $M_z = 0.3301 - 0.01133 (Q_w)$ with a correlation of .63. While the correlation is similar to that for the combined downstream stations there is a significant increase in the slope of the best fit line (Figure 6).

The observed relationships between sediment size parameters and discharge or stream power suggest that the South Fork of the Cache la Poudre in the study area can be divided into two different stream segments in terms of coarse sediment availability and hence bedload sediment movement. Below station C the South Fork of the Cache la Poudre River can best be described in terms of a pool-riffle pattern (Leopold, et al., 1964) which dominates channel form. Although comparatively few studies of coarse sediment transport have been conducted in steep mountain streams, some data are available from Nanson (1974) for the Canadian Rockies and from Hayward (1978) in the mountains east of Christchurch, South Island, New Zealand. Both authors observed that bedload movement was controlled not so much by the hydraulics of the stream as by the availability of material for transport. Under some hydraulic conditions mountain streams are more than competent to transport the material supplied. This appears to be the case in the lower of the two stream segments in the study area along the South Fork of the Cache la Poudre River as seen by a comparison of the regressions between M_z and Q_w for station C and for stations D, E, and F combined (Figure 6). In this stream segment (i.e. D, E, and F), coarser sediment (-0.5 to -2.5ϕ ; 1.41 to 5.6mm) is trapped in pools which are in general armored with cobbles and boulders. The armor and the pool-riffle morphology constitute significant roughness elements that dissipate energy by turbulent mixing. Sediment with a mean size range greater than -0.5ϕ (1.41mm and larger) rarely moves as bedload unless flows equal to, or greater than, 400 cfs occur (Figure 6) or until storage of sediment is sufficient to eliminate the roughness elements (a condition not observed during the study period).

In contrast to these conditions, the stream reach above station C constitutes a relatively low gradient (77 ft/mile) portion of the stream (Figure 2). In this reach the stream meanders through a glacially-filled valley and lateral erosion of bank material provides sediment that accumulates in the channel during the major portion of the year when flows are low. This sediment is flushed out by flood flows associated with spring snowmelt runoff. Sediment

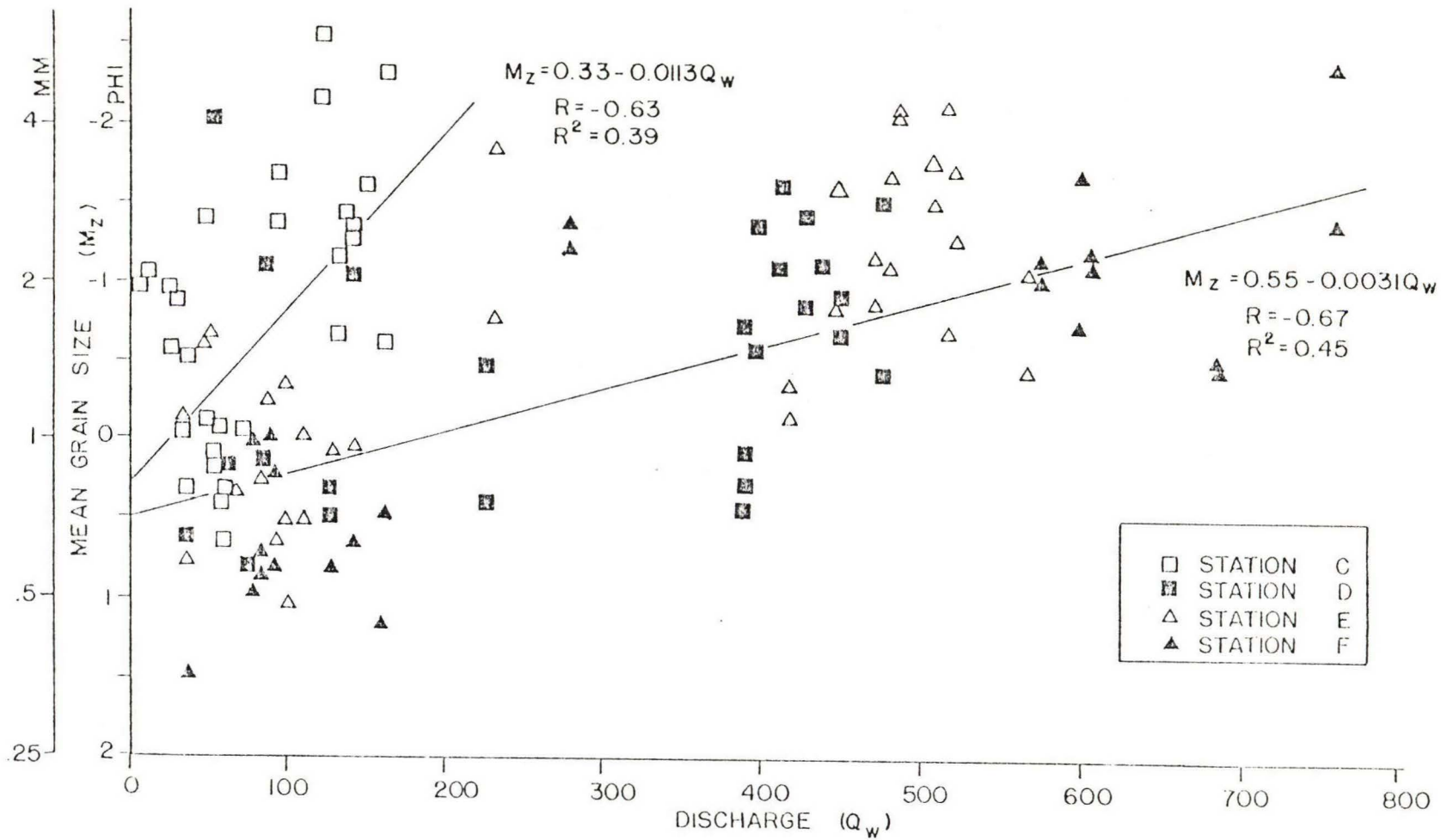


Figure 6. Linear regression of mean grain size (M_z) versus water discharge (Q_w) for station C data and for a combination of stations D, E, and F.

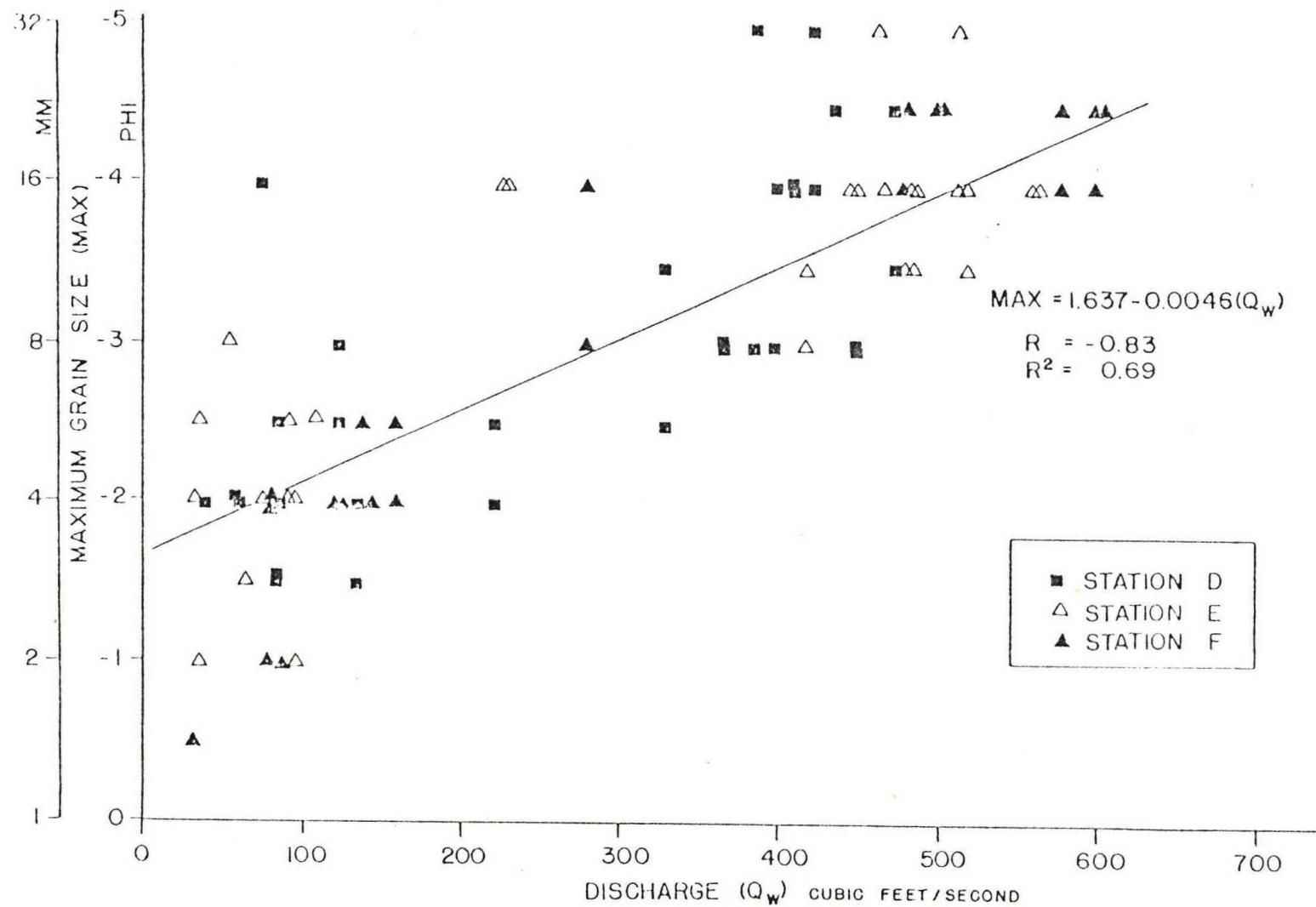


Figure 7. Linear regression of maximum grain size (max) versus water discharge (Q_w) for data from stations D, E, and F.

availability is much greater in this stream reach. Thus, sediment coarser than -0.5ϕ is moved by discharges of less than 200 cfs.

In order to investigate more thoroughly the nature of the relationships between bedload sediment size frequency distributions, water discharge and sediment discharges a number of additional plots were constructed similar to those presented by Hayward (1978). In these graphs the cumulative percentage distributions of bedload sediment, water discharge, and sediment discharge (vertical axis) were plotted against time (horizontal axis). Of the total of eleven plots constructed, three were selected (Figures 8, 9, and 10) to illustrate the variability in particle size distributions throughout the spring runoff period. These graphs reveal several interesting facts concerning the nature of coarse sediment transport in small mountain streams and reconfirm some observations made in the previous section of this report. All graphs show a number of pulses of coarse sediment that move past a given station during the month long period of highest spring runoff. The number of coarse pulses range from 2 to 4 and average 2.5. Except in one case these waves of coarse sediment do not coincide with either peak water or peak sediment discharge values. The highest proportion of coarse sediment generally occurs immediately preceeding or following peak water discharges and on the falling or rising limbs of sediment curves. More often than not the highest proportion of coarse sediment coincides with relatively low values of sediment discharge. Finally, there is no consistent relationship between changes in coarse and finer sediment size fractions. In most instances an increase (or decrease) in the coarsest fraction will result in a corresponding decrease (or increase) in finer size fractions. However, in several instances a decrease in the coarsest size fraction is accompanied by a decrease in the granule and medium to fine sand fraction and a significant increase in the proportion of very coarse to coarse sand. The observations tend to reaffirm our previous conclusion that coarse sediment transport in mountain streams is more a function of sediment availability rather than the shape of the hydrograph or the duration of flood flows (Hayward, 1978). Furthermore, the fact that sediment availability is greater for the stream segment including station C is confirmed by a comparison of Figures 8 and 9. During this 1977 runoff season larger pulses of coarse sediment were moved by smaller discharges at station C. Significantly the largest pulse of coarse material comes at the beginning of the runoff season at station C and only after the peak discharge at station D.

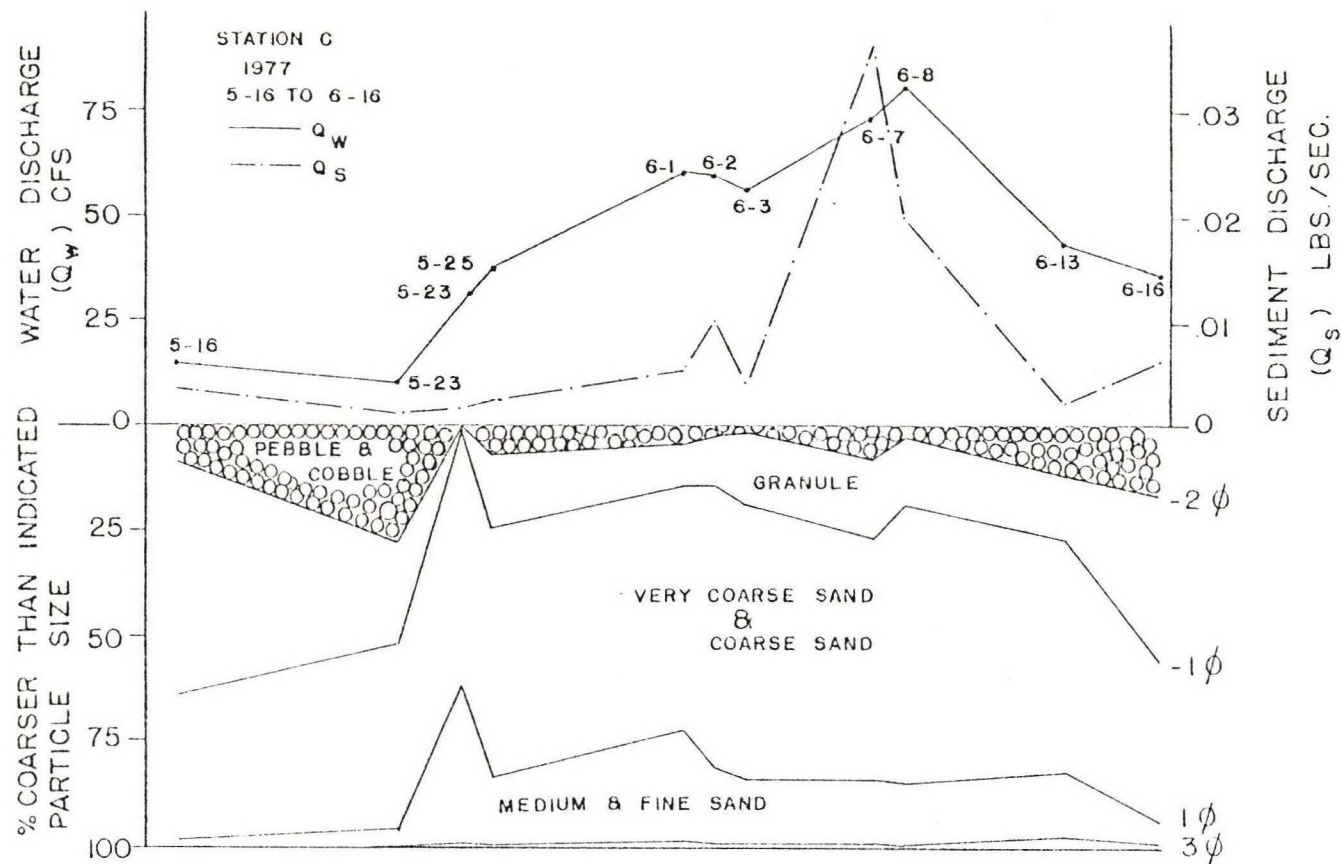


Figure 8. Plot of cumulative grain size frequencies, water discharge (Q_w), and sediment discharge (Q_s) versus time in days for station C; 1977 snow-melt runoff period.

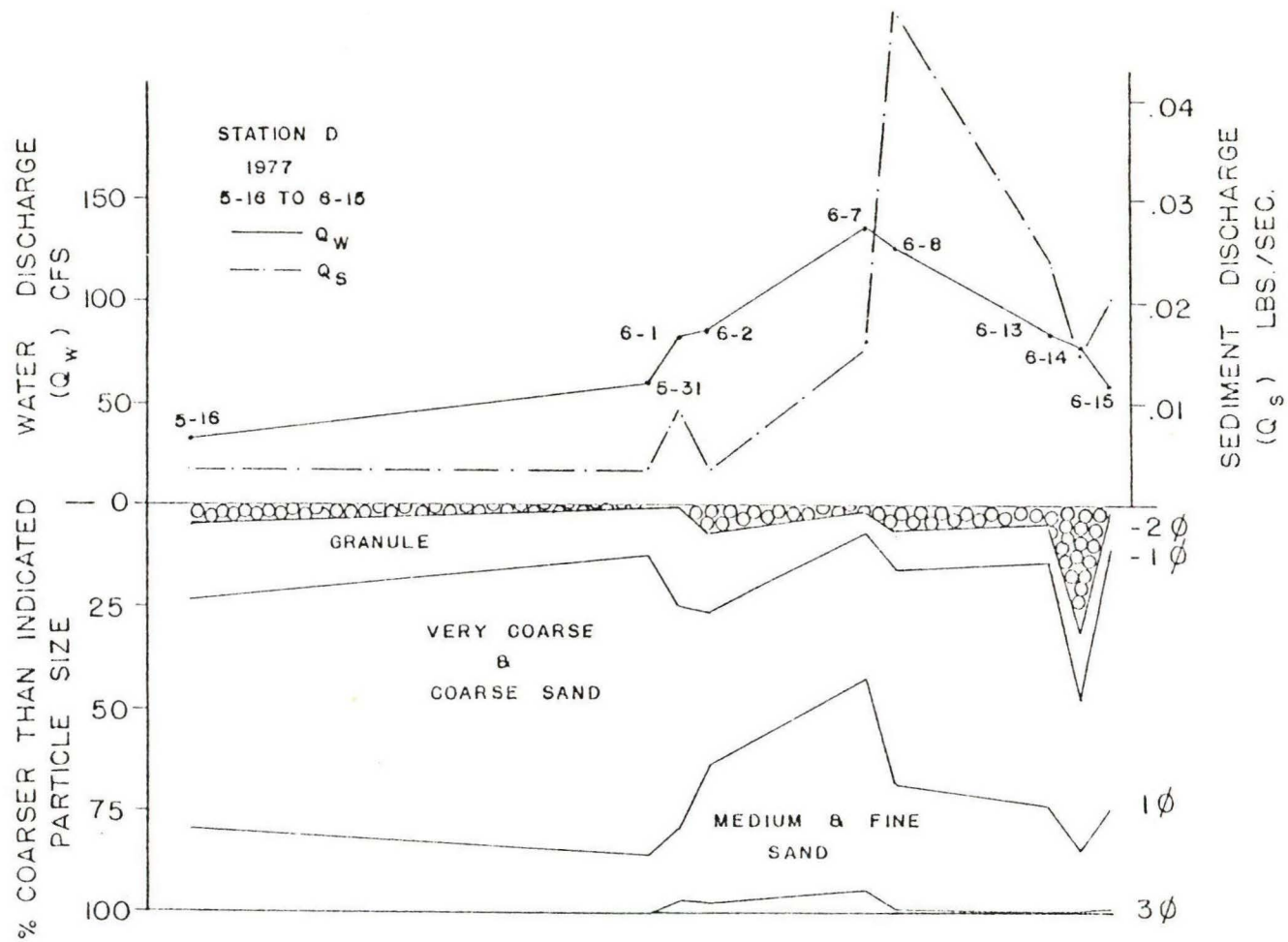


Figure 9. Plot of cumulative size frequencies, water discharge (Q_w), and sediment discharge (Q_s) versus time in days for station D; 1977 snow-melt runoff period.

Factors that have previously been identified as influencing coarse sediment composition and sorting in mountain streams include: 1) dilution of stream detritus by differing source rocks encountered by the channel system and by contributions from tributaries; 2) selective sorting and transport of certain grain sizes as a result of density differences or channel armoring effects; 3) mechanical abrasion; and chemical weathering during temporary storage of detritus. Compositional analyses of the granule, very coarse sand, coarse sand, medium sand, and fine sand fractions of bedload detritus reveals that the relative importance of these processes is a function of grain size. In general, bedload sediment composition is characterized by three populations: 1) a granule and very coarse sediment size fraction, 2) a coarse sediment size fraction, and 3) a medium and fine sand size fraction. The most pronounced variations in bedload composition along the stream are found in the granule and very coarse sand size fractions. These changes result from a combination of factors including the contribution of newly eroded detritus resulting from changes in source terrain, tributary input, and physical destruction of composite grains. Along the glaciated portions of the drainage (above station C) where temporary storage of sediment is occurring, chemical weathering is probably the most important factor affecting the composition of sediment in this population. The coarse sand size fraction is a transitional population. Fluctuations in sediment composition are less evident in this population suggesting that the physical and/or chemical breakdown of detritus from this size fraction approximately equals the contribution of new detritus to this size fraction from the breakdown of coarser detritus. In the medium and fine sand size population significant increases in the content of some mineral components suggests that detritus resulting from the breakdown of simple and composite grains in the larger size fractions is preferentially contributed to this population.

Selective sorting does not appear to be an important process in controlling the bedload composition and/or sorting of pebble to fine sand sizes in mountain streams such as the South Fork of the Cache la Poudre. The lack of a significant relationship between sorting and water discharge, using data from all stations, (Figure 11), emphasizes this conclusion. However, when data from individual, or groups of similar, stations are used, there seems to be a relationship between sorting and discharge, with the best sorting occurring at the lowest discharge (pers. comm., M. Harvey).

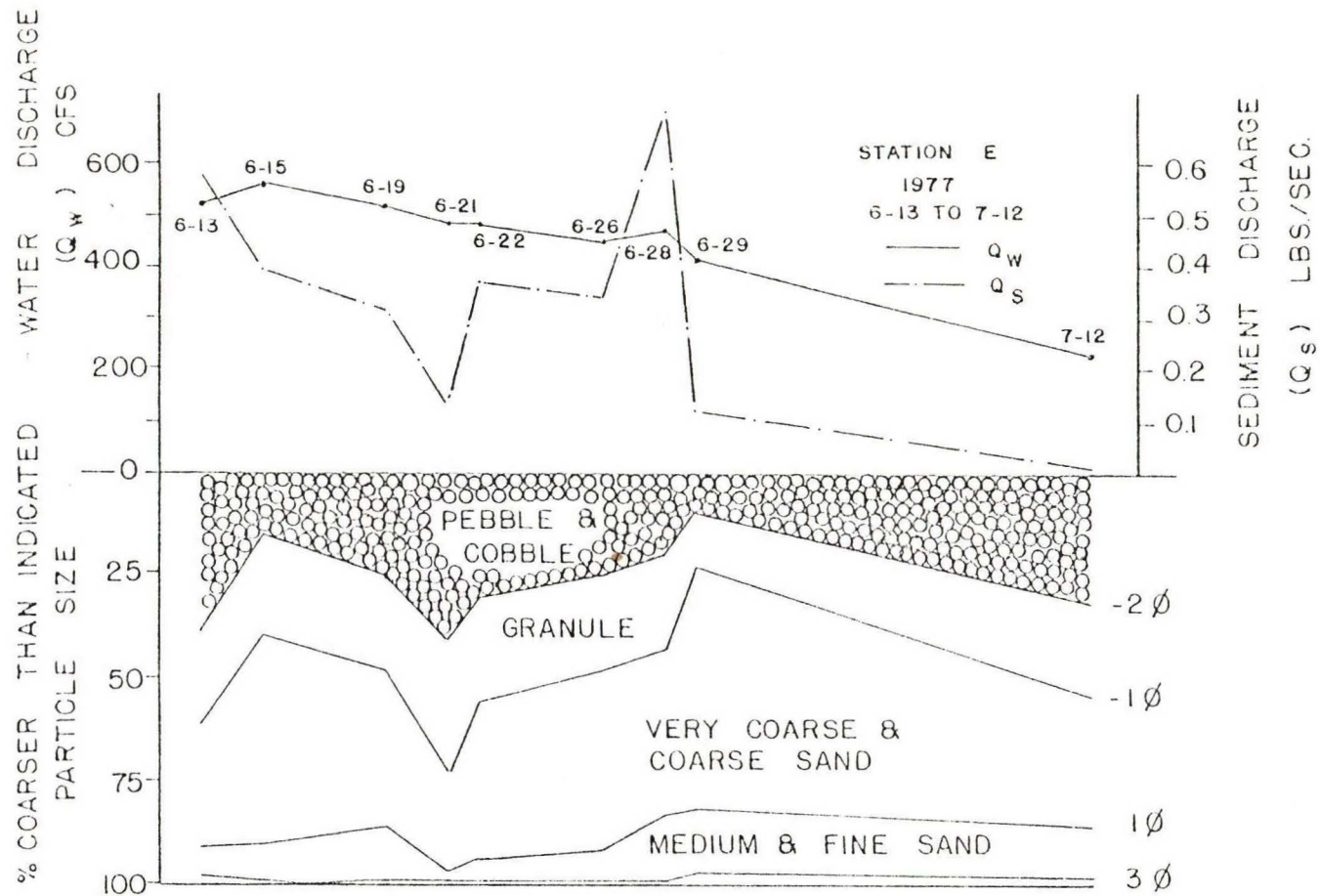


Figure 10. Plot of cumulative grain size frequencies, water discharge (Q_w), and sediment discharge (Q_s) versus time in days for station E; 1978 snow-melt runoff period.

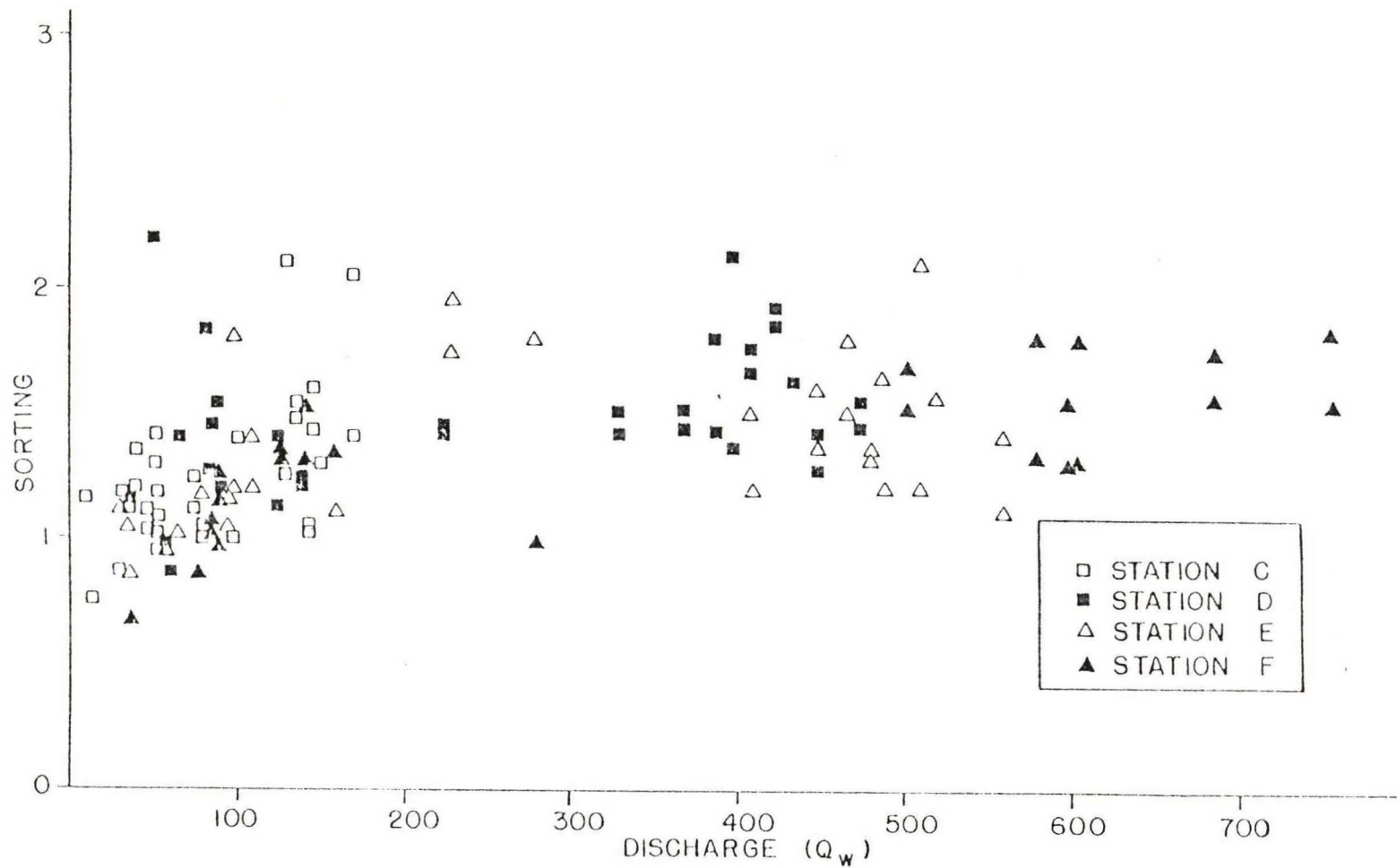


Figure 11. Plot of bedload sediment size sorting versus water discharge; all sample stations; 1977 and 1978 data.

In summary, mean grain size (in phi units) of bedload can be estimated for the lower, nonglaciaded reaches of the South Fork, by $Mz = 0.55 - 0.0031 Q_w$, maximum bedload sizes by, $Max = -1.637 - .0046 Q_w$. For the upper glaciaded reaches, $Mz = 0.330 - 0.01133 Q_w$. Owing to the lack of long-term hydrologic records for the South Fork, reliable flood frequency analysis is not possible. Estimation of discharges for given return periods is possible through the use of regionalization techniques (e.g., McCain and Jarrett, 1976). The above equations can then be applied through the range 1.7 to 754 cfs.

C. Objective 4. Applicability of the Pfankuch-Rosgen channel stability technique.

The application of the Pfankuch-Rosgen channel stability rating method (Pfankuch, 1975) for evaluating the production of bedload was accomplished through the use of Spearman Rank Correlation. The use of a non-parametric test was necessitated by the nature of the channel stability data. Bedload transport rates for the 1977 field season from stations A through F and station P were used. Channels were rated and weighted by length of channel upstream from each station (weighted C.S.) and were ranked (see Table 4). The average bedload discharge was normalized by dividing by average discharge and by taking their base 10 logarithm (i.e., $\log \frac{\bar{Q}_s}{\bar{Q}_w}$). They were also ranked. The Null Hypothesis tested is that of no association between ranked variables. The level of significance chosen was 0.01. The Spearman Rank Correlation computed is $r = 0.96$, which is sufficiently high to reject the Null Hypothesis at $\alpha = 0.01$. The alternative of an association between weighted channel stability and normalized sediment discharge was concluded. This correlation between channel stability rating and observed bedload transport indicates that the channel rating method is applicable to the South Fork of the Cache la Poudre and in all likelihood, to similar streams in the Rocky Mountain Front Range.

<u>Station</u>	<u>Weighted C.S.</u>	<u>Rank</u>	<u>Normalized $\bar{Q}_s$</u>	<u>Rank</u>
A	62	1	-5.02	1
B	64	2	-4.61	2
C	91	6	-3.90	5
D	72	5	-3.79	6
E	68	3	-4.15	3
F	70	4	-3.91	4
P	107	7	-3.54	7

Table 4. Data used for correlation of channel stability rating and sediment discharge.

Additional accomplishments made in connection with this work include:

the construction of a new model for predicting hydraulic roughness in mountain streams (see Appendix),

validation of the precision of Helley-Smith bedload samplers in steep mountain streams,

confirmation of pulsating sediment flow, both short-term (20-30 minutes in period) and long-term (during the snowmelt period),

and providing research opportunities for four Master of Science candidates, Mss. Henry DeWitt, David Haddock, Richard Moore, and Donald Simpson.

REFERENCES CITED

- DeWitt, H. G., 1978, Downstream changes in bedload composition, Little South Fork and Cache la Poudre Rivers, Colorado: unpublished M.S. Thesis, Colorado State University, 131 p.
- Draper, N. R. and Smith, H., 1966, Applied Regression Analysis: John Wiley and Sons, Inc., New York, 407 p.
- Einstein, H. A., 1964, River Sedimentation: in Handbook of Applied Hydrology, V. T. Chow (ed.), McGraw-Hill Book Co., New York.
- Haddock, D. R., 1978, Modeling bedload transport in mountain streams of the Colorado Front Range: unpublished M.S. Thesis, Colorado State University, 74 p.
- Hayward, J. A., 1978, Hydrology and stream sediments in a mountain catchment: unpublished Ph.D. dissertation, University of Canterbury, New Zealand, in three volumes.
- Houston, R., 1968, A regional study of the rocks of Precambrian age in that part of the Medicine Bow Mountains lying in Southeastern Wyoming: Geol. Survey of Wyo., Mem. 1, 167 p.
- Leopold, L. B., Wolman, M. G., and Miller, J. P., 1964, Fluvial Processes in Geomorphology: W. H. Freeman and Co., San Francisco, 522 p.
- Lovering, T. S., and Goddard, E. N., 1950, Geology and ore deposits of the Front Range, Colorado: U. S. Geol. Survey Prof. Paper 223, 319 p.
- Lustig, L. K., 1965, Sediment yield of the Castaic watershed, western Los Angeles County--A quantitative geomorphic approach: U. S. Geol. Survey Prof. Paper 422-F, 23 p.
- Madole, R. F., 1969, Pinedale and Bull Lake glaciation in upper St. Vrain drainage basin, Boulder County, Colorado: Arctic and Alpine Research, v. 1, no. 4, p. 279-287.
- Meyer, Peter E., and Müller, R., 1948, Formulas for bedload transport: Int. Assoc. for Hydraulic Res., Stockholm.
- McCain, J. F., and Jarrett, R. D., 1976, Manual for estimating flood characteristics of natural-flow streams in Colorado: Tech. Man. 1, Colo. Water Conserv. Board, 68 p.
- Nanson, G. C., 1974, Bedload and suspended load transport in a small, steep, mountain stream: Am. Jour. Sci., v. 274, p. 471-486.
- Pfankuch, D. J., 1975, Stream reach inventory and channel stability evaluation: U. S. Dept. Agric., Forest Service, Northern Region, 26 p.
- Schoklitsch, A., 1934, Der Geschriebtreib und die Gescheibfract: Wasserkraft und Wasserwirtschaft, p. 37-43.
- Simons, D. E., and Santürk, F., 1977, Sediment transport technology: Water Res. Pub., Fort Collins, Colorado, 807 p.
- Simpson, D. H., 1978, Modeling of bedload transport and hydraulic roughness in mountain streams: unpublished M.S. Thesis, Colorado State University, 85 p.

APPENDIX

Published abstracts resulting from this project.

1. Fall Meeting, 1977, American Geophysical Union.

ESTIMATION OF MANNING'S "n" FOR STEEP MOUNTAIN STREAMS USING FABRIC ANALYSIS

D.H. Simpson

D.O. Doehring (Department of Earth Resources,
Colorado State University, Fort Collins, CO.
80523)

Accurate estimation of Manning's "n" for high gradient streams has been a long standing problem. Many of the equations which relate channel roughness to grain size and relative roughness were developed on low gradient, armored, alluvial channels and decrease in usefulness when applied in mountain settings. Work on the South Fork of the Cache La Poudre River, in the Colorado Front Range, suggests that hydraulic radius, slope, and fabric of the coarsest 15 to 25 percent of the channel armor provide improved estimates of roughness through the following relationship,

$$n = f\left(\frac{\phi S}{R}\right),$$

where n, S, and R represent Manning's roughness coefficient, slope of the energy surface and hydraulic radius respectively. ϕ is a fabric parameter and includes elements of size, shape and orientation. It is measured using a Zeiss Particle Analyzer (or similar device such as an optical scanner) and specially prepared photographic images. Careful selection of the in situ cobble armor to be measured and choice of the range of grain sizes that affect channel roughness is necessary to optimize the effectiveness of the method.

1. 032740DOEHRING

2. 1977 Fall Meeting

3. Hydrology

4. None

5. No

6. No

7. 0%

8. Bill to:

D.O. Doehring
Department of Earth Resources
Colorado State University
Fort Collins, Co. 80523

2. 1978 Conference, American Water Resources Association.

ESTIMATION OF HYDRAULIC ROUGHNESS IN STEEP MOUNTAIN STREAMS

Donald O. Doehring*, Donald H. Simpson and Richard C. Moore,
Department of Earth Resources, Colorado State University

Modeling the behavior of mountain streams is complicated by the difficulty of accurately estimating hydraulic roughness. Many of the existing equations relate roughness to grain size and were developed from empirical data obtained on low gradient, alluvial streams. They decrease in usefulness when applied to the steep, bedrock channels common to mountainous areas.

Work on the South Fork of the Cache la Poudre River in the Front Range of the Colorado Rockies suggests that hydraulic radius (R), slope of the energy surface (S) and fabric (ϕ) of the coarsest 15 to 25 percent of the channel armor can be used to provide improved estimates of the Chezy coefficient (C) using the relationship,

$$C = f\left(\frac{\phi S}{R}\right).$$

The fabric parameter (ϕ) is a measure of flow resistance created by channel armor and reflects the size and shape of clasts as well as their orientation relative to streamflow. These in situ measurements are taken from specially prepared photographs of the streambed. Our methods eliminate or substantially reduce errors accruing from sieving, clast orientation and sampling. The resulting estimates appear to be superior to those yielded by standard equations.

3. Fall Meeting, 1978, American Geophysical Union.

MODELING BEDLOAD TRANSPORT IN STEEP MOUNTAIN STREAMS OF THE COLORADO FRONT RANGE

D. R. Haddock

D. O. Doehring (both at: Dept. of Earth
Resources, Colorado State Univ., Fort Collins,
Colorado 80523)

Field studies conducted on two steep gradient mountain streams in the Northern Colorado Front Range area have shown that traditional bedload formulas, eg., Schoklitsch (1934) and Meyer-Peter and Müller (1948), may be undesirable for use in this high energy/limited sediment supply environment. As alternatives, three multiple linear regression equations have been developed on the Little South Fork of the Cache la Poudre River and field tested on the Middle and South Forks of the St. Vrain River. The equations developed use both quantitative geomorphic and hydraulic parameters to model the response variable, and have R^2 values ranging from 68 to 77%. The standard errors of the estimate, presented as a percentage of the mean response, range from 27 to 31%. Based on model simplicity and sensitivity analysis of the independent variables with respect to the model response, the best equation is:

$$\log Q_s = -5.97 + 1.45 (\log Q_w) + .35 (D_d),$$

where Q_s is the bedload discharge (lbs/sec), Q_w is the water discharge (cfs) and D_d is the drainage density (miles/square mile). Associated R^2 and standard error of estimate for this equation are 68% and 31%, respectively. When tested against observed values within the St. Vrain watershed this equation predicts very well. All observed bedload discharges fall within the 95% confidence interval for the predicted bedload discharge. In the worst case, the model underpredicts the observed values by 60% which compares very favorably with bedload computed by either the Schoklitsch or Meyer-Peter and Müller formulas which overpredict by orders of magnitude. The assumption of unlimited sediment supply that underlies both traditional formulas appears to be the major cause for these overpredictions.

1. 03274Doehring
2. 1978 Fall Meeting
3. Hydrology
4. None
5. No
6. No
7. 0%
8. Bill to:
D. O. Doehring
Dept. of Earth Resources
Colorado State University
Fort Collins, CO 80523